OFDM-MSK: A Method for Sidelobe Suppression in OFDM Systems

S. Mahmoodi [1], H. Saeedi [2], M.J. Omidi [3]

#*ECE Dep., Isfahan University of Technology, Isfahan, Iran*

[1]smahmoodi@ec.iut.ac.ir, [2]saeedi@ec.iut.ac.ir, [3] omidi@cc.iut.ac.ir

***Abstract*— Orthogonal frequency division multiplexing (OFDM) systems suffer from high sidelobes level. In some applications, as cognitive radios, this phenomenon can be a serious matter. This paper proposes Minimum shift keying (MSK)-OFDM to address this problem. The proposed method is an OFDM system using MSK modulation in each subcarrier. The corresponding transmitter and receiver are introduced. The method doesn't entail great changes in the main parts of OFDM. Like OFDM systems, the transceiver can be implemented using DFT/IDFT. Simulation results show great reduction in out of band radiation in comparison with conventional OFDM.**

I. Introduction

Orthogonal frequency division multiplexing (OFDM) is the most widely used multicarrier technique in wireless communications. It has been used in 802.11a/g, digital video broadcasting (DVB), digital audio broadcasting (DAB), and 802.16a standards successfully. It is also proposed for Long-Term Evolution (LTE)[1]. OFDM divides spectrum into some subcarriers which enables high data rate transmission. It provides robustness against frequency selective channel using cyclic prefix (CP). This makes equalization indeed simple using one complex-tap at the receiver. In addition, OFDM can be implemented with DFT/IDFT efficiently. The simplicities involved in OFDM design and implementation make OFDM cost-effective and consequently popular.

Despite these advantages, OFDM has some disadvantages. One of the main drawbacks of OFDM is its high sidelobe level. The high sidelobe level makes OFDM usage difficult in some circumstances. In OFDM-based Cognitive Radios high out of band radiation of unlicensed users doesn't meet the acceptable interference level requirements of the legacy system. Moreover, high sidelobe level makes OFDM sensitive to carrier frequency offset (CFO) and causes inter carrier interference (ICI). The problem becomes more serious in uplink of Orthogonal frequency division multiple access (OFDMA) [2]. One can conclude that it is necessary to reduce the side lobe level.

The out of band radiation reduction has been studied extensive in the literature [3]-[8]. Windowing in time domain and deactivating some carriers located in the edge of the used band are first solutions proposed [3]. Windowing smoothes symbol transitions and thus reduces the out of band radiation. the deactivating edge carrier method is based on the fact that these subcarriers are more responsible for high sidelobe level than inner subcarriers. In this method in order to reduce sidelobe levels, these carriers aren't used for data transmission. A similar method, subcarrier cancellation, proposes edge subcarriers aren't used for data transmission but they are so weighted that minimizes out of power in the optimization region frequencies [4]. Subcarrier weighting method weights all subcarriers and uses even edge subcarriers for data transmission [5]. A similar method adds complex sequences to the data which are to modulate subcarriers [6]. subcarrier weights and the additive sequences are determined according to an optimization problem for each OFDM symbol in these methods. The adaptive symbol transition is similar to windowing but it adaptively weights the OFDM samples located at the edge of OFDM symbols [7]. This way symbol transition are so determined that the out of band components are minimized. Like previously mentioned methods this method needs to calculate transitions weights for every OFDM symbol. The suboptimal subcarrier cancellation technique and constellation expansion are other methods used for the sidelobe level problem [8]. The former tries to reduce complexity of subcarrier cancellation method without significant degradation in performance and the latter expands the constellation (i.e. it uses a constellation with two times numbers of points); for each subcarrier, a specific input corresponds to two points in the constellation; for each OFDM symbol, the recursive algorithm searches through possible sequences from the two constellation to select a state which guarantees the out of band radiation isn't more than a determined threshold.

To our best knowledge, non of above methods can solve the out of band radiation properly. Windowing and deactivating edge subcarriers method waste the resources in time and frequency, respectively and they aren't so effective in the sidelobe suppression [8]. Subcarrier weighting, additive sequence, and adaptive symbol transition suffer from high complexity. Furthermore, Adaptive symbol transition method reduces effective data rate due to adding some samples to the each OFDM symbol for weighting. Besides, most methods degrade BER performance. Our goal in this paper is to propose a proper method to reduce the out of band radiation.

One determined point for high sidelobe level is the sudden changes in symbol transitions in conventional OFDM. Suppose binary phase shift keying (BPSK) is used in each subcarrier; if a 1 precedents a -1 in input bit stream, the phase of the corresponding subcarrier can change 180 degrees in OFDM symbol transition. The phenomenon brings high frequency components that intuitively are out of band. Such an idea moved us to use a continuous phase modulation (CPM) instead of, for example, BPSK in each carrier to prevent the subcarrier phase jumping in the symbol transitions. A smaller group of CPM is continuous phase frequency shift keying (CPFSK). A special case of CPFSK modulation is minimum shift keying (MSK) which is used successfully in global system for mobile communications (GSM) standard as a Gaussian MSK (GMSK). MSK is a frequency shift keying (FSK) modulation that uses two frequencies for data transmission. The frequency space between carriers is $1/2T$, where $1/T$ is the symbol rate.

MSK has different forms; in other words for a given input stream, some different output signals are possible and all have MSK above properties such as carrier phase continuity and the subcarriers spacing. One form that was introduced by Passupathy in [9] looks at MSK as an offset QPSK (OQPSK); it uses sine and cosine pulse shapes to reach a higher spectral efficiency with respect to OQPSK. We use such an MSK outlook in our method. Another view is looking at MSK as an special case of CPFSK, i.e. CPFSK special parameters are so determined to result in an MSK signal with mentioned properties [10]. There are more forms for MSK.

Using MSK with OFDM is existed in literature in [11] and [12]. The structure in [11] is completely different from our approach. Unlike us, it doesn't use MSK modulation for each subcarrier. It uses a so-called multi-amplitude MSK to reduce PAPR. Although [12] exploits MSK modulation in every subcarrier, the type of its MSK is different from ours. We use MSK as an OQPSK. Whereas [12] looks at MSK as a CPFSK signal. It is shown in subsequent sections of the paper using OQPSK with sinusoidal pulse shaping view of MSK ends in simpler structure for the receiver. Reference [12] needs 4 DFT blocks and N Viterbi sequence detectors (N is the number of subcarriers) in the receiver.

OFDM-MSK is proposed as a new structure for multicarrier systems. Having many benefits of conventional OFDM, it reduces sidelobe levels significantly.

This paper is organized as follows. Section II describes system model which we designed for the transmitter and receiver of OFDM-MSK. The system implementation with IDFT and DFT is also presented. Section III presents simulation results.

II. SYSTEM MODEL

MSK is a single carrier modulation that is attractive for its high spectral efficiency. It has good bit error rate (BER) performance when compared to BPSK [9]. It also has phase continuity at bit intervals. Its demodulation and synchronization circuits are simple [9]. In addition, because it has a constant envelop, it is of great interest in special channels. Before describing the multicarrier MSK, it is worthy to look into the MSK signal thoroughly. The input stream $a(t)$ is multiplexed into two streams $a_o(t)$ and $a_e(t)$, where $a_e(t)$ is shifted T seconds with respect to $a_o(t)$ to end in mentioned properties of MSK. Then $s(t)$ is [9]

$$\begin{aligned} s(t) =& a_e(t)\cos\left(\frac{\pi t}{2T}\right)\cos\left(2\pi f_c t\right) + \\ & a_o(t)\sin\left(\frac{\pi t}{2T}\right)\sin\left(2\pi f_c t\right) \end{aligned} \quad (1)$$

An MSK signal can be viewed as a FSK modulation, because it uses two different frequencies for data transmission. It is showed that the space between the two frequencies is half the bit rate. This is the minimum frequency spacing required to enable us detect signals coherently. The term minimum shift stands for it.

OFDM-MSK is a multicarrier system which uses MSK in each subcarrier. In a single carrier MSK, in order to make carrier phase continuous at bit transitions, the carrier frequency must be an integral multiple of $1/2T$ [9], where $1/T$ is symbol rate; $1/4T$. However, in a multicarrier MSK for the data is recoverable at the receiver, another condition is necessary. It can be shown that the carrier spacing needs to be an integral multiple of $1/T$ (Note that under this condition carriers are orthogonal in every interval T seconds).

A. *OFDM-MSK Transmitter*

The OFDM-MSK transmitter is represented in the Fig. 1.a The transmitted OFDM-MSK signal can be formulated as

$$x(t) = x_e(t) + x_o(t), \quad (2)$$

where

$$x_e(t) = \sum_{l=-\infty}^{+\infty}\sum_{k=0}^{N-1} a_{2l}^k(-1)^l h(t-2lT)\cos\left(\frac{2\pi kt}{T}\right) \quad (3)$$

and

$$x_o(t) = \sum_{l=-\infty}^{+\infty}\sum_{k=0}^{N-1} a_{2l+1}^k(-1)^l h(t-2lT-T)\sin\left(\frac{2\pi kt}{T}\right) \quad (4)$$

where k and l are the subcarrier and input data stream indexes, $a_l \in \pm 1$, and $h(t)$ is

$$h(t) = \begin{cases} \cos\left(\frac{\pi t}{2T}\right), & -T \le t \le T; \\ 0, & \text{O.W.} \end{cases} \quad (5)$$

By some mathematical manipulations of (3) and (4), $x(t)$ in (2) can be rewritten as

$$\begin{aligned} x(t) = \sum_{l=-\infty}^{+\infty}\sum_{k=0}^{N-1} \Re\Big\{ & \left(a_{2l}^k(-1)^l h(t-2lT) - \right. \\ & \left. j a_{2l+1}^k(-1)^l h(t-2lT-T)\right) e^{\frac{j2\pi tk}{T}} \Big\} \end{aligned} \quad (6)$$

B. *OFDM-MSK Receiver*

Figure 1.b depicts OFDM-MSK receiver. The proposed structure for Multicarrier MSK is equivalent to applying single carrier MSK demodulator introduced by Passupathy [9] in each subcarrier. The received signal is demodulated and passes through filters $h(t-T)$ and $h(t)$ to recover symbols with odd

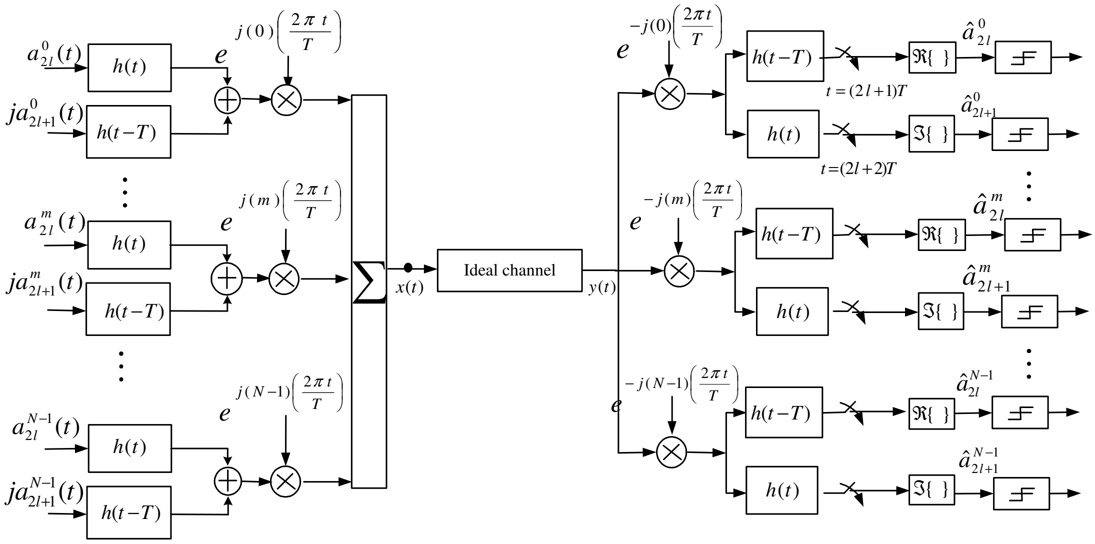

Fig. 1. The baseband representation of OFDM-MSK transceiver (a) Transmitter (b) Receiver

and even indices. Then filtered signals are sampled and go to $\Re\{\}$ and $\Im\{\}$ functions.

The estimated data symbols on the mth subcarrier are equal to

$$\begin{cases} \hat{a}_{2l}^m = \Re\left\{y(t)e^{\frac{-j2\pi mt}{T}} \star h(t-T)\right\}, & ; \\ \hat{a}_{2l+1}^m = \Im\left\{y(t)e^{\frac{-j2\pi mt}{T}} \star h(t)\right\}, & . \end{cases} \quad (7)$$

where $y(t)$ is the received signal.

It is worth noting that the transceiver can be implemented using DFT/IDFT easily. This way it is put into practice with a less complexity.

C. ISI and ICI Free Transmission

While the channel is ideal, We have

$$\begin{cases} \hat{a}_{2l}^m = a_{2l}^m, \\ \hat{a}_{2l+1}^m = a_{2l+1}^m. \end{cases} \quad (8)$$

Extending the first row in (7) results in

$$\hat{a}_{2l}^m = \int_{-\infty}^{+\infty} \sum_{k=0}^{N-1} \sum_{l_1=-\infty}^{+\infty} \left(a_{2l_1}^k (-1)^{l_1} h(\tau - 2l_1 T) \cos\left(\frac{2\pi k\tau}{T}\right) + a_{2l_1+1}^k (-1)^{l_1} h(\tau - 2l_1 T - T) \sin\left(\frac{2\pi k\tau}{T}\right) \right) \times h(T-t+\tau) cos(\frac{2\pi m\tau}{T}) d\tau|_{t=(2l+1)T} \quad (9)$$

Since $h(t)$ is time limited in $-T \le t \le T$, the sigma in (9) can be simplified and break into only three sections. Using addition and subtraction formulas for sine and cosine, these sections can be evaluated as,

$$\int_{(2l-1)T}^{2lT} \sum_{k=0}^{N-1} \left(\frac{-a_{2l-1}^k}{2}\right) \sin\left(\frac{2\pi k\tau}{T}\right) \times \cos\left(\frac{2\pi m\tau}{T}\right) \sin\left(\frac{\pi\tau}{T}\right) d\tau = 0, \quad (10)$$

,

$$\int_{2lT}^{(2l+1)T} \sum_{k=0}^{N-1} \left(\frac{a_{2l+1}^k}{2}\right) \sin\left(\frac{\pi k\tau}{T}\right) \times \sin\left(\frac{2\pi k\tau}{T}\right) \cos\left(\frac{2\pi m\tau}{T}\right) d\tau = 0, \quad (11)$$

, and

$$\int_{(2l-1)T}^{(2l+1)T} \sum_{k=0}^{N-1} \left(a_{2l}^k\right) \cos\left(\frac{2\pi k\tau}{T}\right) \times \cos^2\left(\frac{\pi\tau}{2T}\right) \cos\left(\frac{2\pi m\tau}{T}\right) d\tau = \frac{a_{2l}^m}{2}, \quad (12)$$

Infact, because transmission of a_{2l-1}^m and a_{2l+1}^m are overlapped with that of a_{2l}^m, the expressions (10) and (11) can be remained from the sigma over l_1.The fact that $h(t)$ is time-limited omits sections related to other values l_1. The second row of (8) can be proved similarly.

III. Simulation Results

In this section, simulation results are presented. power spectral density of MSK and OFDM Conventional OFDM if only one carrier is used, are depicted Fig. 3. The Figure shows high power spectral efficiency of MSK. The largest sidelobe of MSK is around 10 dB less than OFDM. Conventional OFDM and OFDM-MSK system with 64 subcarriers are simulated. In our simulation T is considered 0.1 ms. Figure 3compares the power spectral density for the two systems. Simulaion shows OFDM-MSK can suppress sidelobe level by 39 dB.

While other previous techniques got into serious trouble with increasing number of subcarriers, OFDM-MSK complexity increases linearly. In subcarrier weighting, insertion of cancellation carriers, additive signal, and adaptive symbol transition methods the computation due to optimization algorithms becomes very high. For example in subcarrier weighting in which subcarriers used for data transmission are weighted, doubling the number of carriers makes the optimization problem dimension doubled and, in turn, causes the system complexity increases exponentially. Similarly in constellation expansion method increasing the number of the subcarriers results in exponentially increasing of computational complexity. Note that these high complex computations are executed for each OFDM symbol.

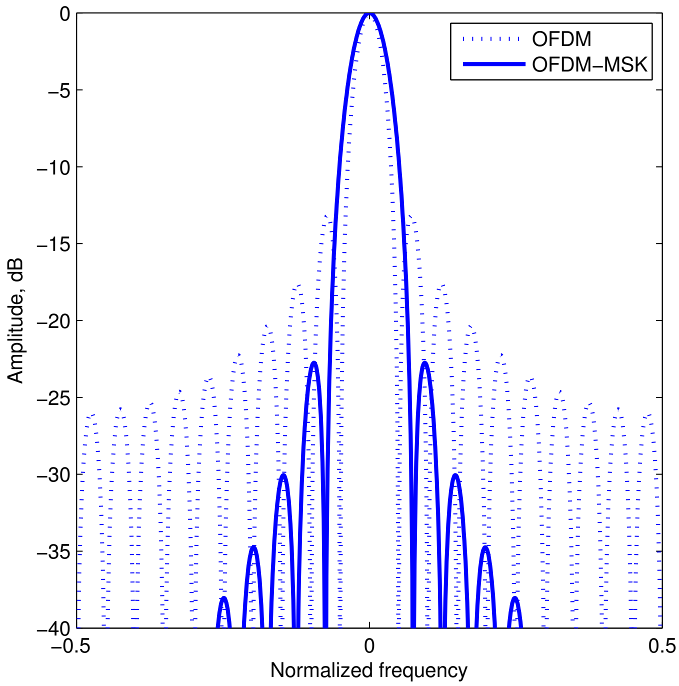

Fig. 2. The baseband representation of OFDM-MSK transceiver

IV. Conclusions

In this paper, OFDM-MSK technique has been proposed for sidelobe reduction in OFDM systems. Corresponding transmitter and receiver have been designed. It has been proved information is recoverable without any ISI or ICI if channel is perfect. Simulation results showed that OFDM-MSK can reduce sidelobe level by 39 dB with respect to conventional OFDM. As far as the autors know, the other existing methods haven't reported such reduction. Unlike some available methods for out of band radiation reduction, OFDM-MSK complexity increases linearly with increasing number of subcarriers. OFDM-MSK caused insignificant PAPR increasing.

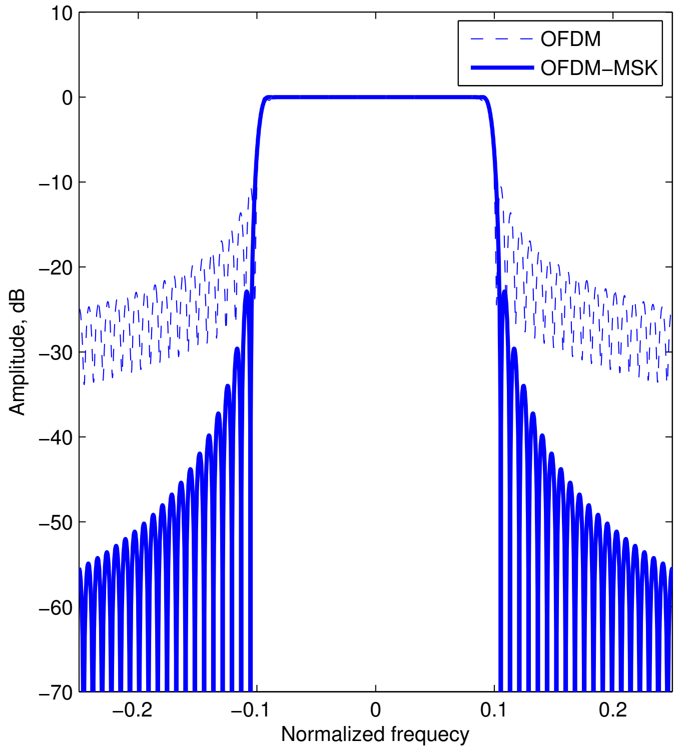

Fig. 3. The baseband representation of OFDM-MSK transceiver

References

[1] A. Larmo, M. Lindstrom, M. Meyer, G. Pelletier, J. Torsner, and H. Wiemann, "The LTE link-layer design," *IEEE Communications Magazine,* vol. 47, no. 4, April 2009, pp. 52-59.

[2] B.M. Morelli, C.C.J. Kuo, and M.N. Pun, "Synchronization techniques for orthogonal frequency division multiple access (OFDMA): A tutorial reveiew, " in *proc. of the IEEE*, vol. 95, no. 7, pp. 1394-1427, July 2007.

[3] T. Weiss, J. Hillenbrand, A. Krohn, and F. Jondral, "Mutual interference in OFDM-based spectrum pooling systems, " in *Proc. VTC conf.*, vol. 4 , no. , pp. 1873-1877 , 2005.

[4] S. Brandes, I. Cosovic,and M. Schnell, "Reduction of out-of-band radiation in OFDM systems by insertion of cancellation carriers," in *IEEE Communication Letters*, vol. 10, no. 6, pp. 420-422, 2006.

[5] I. Cosovic, S. Brandes, and M. Schnell, "Subcarrier weighting: a method for sidelobe suppression in OFDM systems," in *IEEE Communication Letters*, vol. 10, no. 6, 2006

[6] I. Cosovic, and T. Mazzoni, "Sidelobe suppression in OFDM spectrum sharing systems via additive signal method," in *Proc. VTC conf.*, vol. 25, no. 28, pp. 2692-2696, 2007.

[7] H. A. Mahmoud, and H. Arslan, "Sidelobe suppression in OFDM-Based spectrum sharing systems using adaptive symbol transition," in *IEEE Communication Letters*, vol. 12, no. 2, 2008.

[8] S. Pagadarai, Sidelobe suppression for OFDM based cognitive radios in dynamic spectrum access networks, MSc. thesis, Department of Electrical Engineering and Computer Science, University of Kansas, 2007.

[9] S. Pasupathy, "Minimum Shift Keying: a spectrally efficient modulation, " *IEEE Communications Magazine,* vol. 17, no. 4, pp. 14-22,1979.

[10] J. G. Proakis, Digital communication, McGraw-Hill, 4th edition, 2000.

[11] A.E. Ashraf, R. M. adel, A. Elsherbini, I.D. Moawad , and A. I. Abdelfattah "Performance of Multi-Amplitude Minimum Shift Keying (N-MSK) with Orthogonal Frequency Division Multiplexing (OFDM)," EUROCON 2007 The International Conference on "Computer as a Tool" 1057-1060

[12] R.H.-H. Yang, Sh.-J. Chern, Ch.-Ch. Tseng, and Zh.-H. Zhan,"OFDM-MSK for wireless communications," Proc. International Symposium on Intelligent Signal Processing and Communication Systems ISPACS, pp. 269-272, 2005.